INVESTIGATION OF THE VISCOELASTIC PROPERTIES OF A WATER-SATURATED SEDIMENT

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OF A WATER-SATURATED SEDIMENT

by

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ABSTRACT

Experiments were made in the laboratory to determine the feasibility of adapting to the measurement of the shear elastic properties of sediment-like materials techniques already proven for use on viscoelastic liquids. A torsional transducer attached to an aluminum rod was immersed in a Kaolin sediment and driven in either a pulse-echo mode or a standing wave mode. Both techniques were found to be satisfactory and in good agreement over the limited frequency range (38 to 39 kHz) imposed by the characteristics of the transducer-rod combination. In the pulsed mode, measurement of the changes in attenuation and phase of the pulses (tone-bursts) in the rod when the rod is immersed in the sediment allow calculation of the real and imaginary parts of the complex shear modulus. In the resonant mode, measurement of the changes in resonant frequency and the electrical resistance at resonance upon immersion allow a similar calculation of the complex shear modulus. It was found that a complex shear modulus did exist for the sediment investigated, thus indicating that the sediment displays both viscous and elastic properties. Furthermore, the measured properties were found to

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1. Introduction

The propagation of sound in shallow water and the effectiveness of the bottom bounce mode of sonar operation are sensitive to the acoustic properties of the bottom materials. Some knowledge of these properties is essential to the construction of a realistic model of the sea floor.

In the general and usually complicated case where a compressional wave is incident upon the interface between two media, satisfaction of the boundary conditions requires the existence of both reflected and transmitted compressional and transverse (shear) waves (2). In the special and much simpler case of a liquid-liquid interface the shear waves cannot exist. In the special case of a liquid-solid interface, in addition to the reflected and transmitted compressional waves, a transmitted transverse wave is required. Thus, determination of the nature of the ocean bottom sediments (i.e. liquid, solid, or semi-solid) will aid in predicting what waves will be transmitted into the sediments and what losses will occur.

Many of the existing theories of acoustic reflection processes have used a multilayer fluid model in which only longitudinal (compressional) waves can exist. In some cases it has been necessary to assume a bottom which has the elastic properties of a solid in order to get reasonable agreement with experiment (1,12). Therefore, it appears that some knowledge of the shear elasticity in sediments should be obtained.

Most of the methods devised thus far have calculated the shear elasticity of sediments from measurements of the propagation velocity of longitudinal waves. To the best of our knowledge no direct measurements of the shear elasticity of sediments have been made at frequencies

in the kHz range.

The purpose of this research was to determine the feasibility of adapting instrumentation which had been used in viscoelastic measurements in fluids (11) to the measurement of these properties in sediment-like materials.

2. Theory and Method of Measurement

a) General

The measurement method involves determining the reaction of the sediment material to an oscillating shear motion generated by torsional waves in a long metal rod imbedded in the sediment. Two techniques for this determination were used: (1) a pulse-echo method using traveling waves, and (2) a standing wave (resonance) method. In both techniques the properties of the sediment are analyzed in terms of the complex mechanical impedance of the sediment to the oscillating shear motion.

b) Pulse Method

The method uses a piezoelectric torsional transducer cemented to an aluminum rod to excite a short train of torsional waves in the rod and to receive the reflected pulses from the free ends of the rod. The pulse will undergo an attenuation and phase shift in traveling down the rod. Surrounding the rod with the sediment will introduce added attenuation and phase shift due to its mechanical load impedance.

Following the method used by Prather (11) the mechanical impedance of the sediment is obtained by assuming plane shear waves of the form $u_x = U_0 e^{-\alpha z} e^{j(\omega t - \alpha z)}$ propagating into an infinite medium. In the above x is the direction of particle motion parallel to the plate, z is the direction of propagation perpendicular to the plate, U_0 is the initial amplitude, ω is the angular frequency, and α is a spatial

decay constant given by $\alpha = \sqrt{\frac{\omega \rho_{SED}}{2\eta}}$ where ρ_{SED} and η are the density and viscosity of the sediment. If we assume that the sediment investigated is a liquid with a flow viscosity of less than one poise, that the frequency is greater than 30 kHz and that the density is greater than 1 gram per cubic centimeter, then the shear wave is attenuated to $1/e$ of its initial value in less than 0.003 centimeters from the surface of the rod. Since the shear wave is attenuated in such a short distance as compared to the radius of the rod (0.645 centimeters) the assumption of plane waves is justified. The attenuation distance is also much smaller than the distance between the rod and inside radius of the water jacket so that wall effects may be ignored.

The specific acoustic load impedance, defined as the ratio of shear stress to tangential particle velocity, for these (plane) shear waves is given by

$$Z = \sqrt{\pi f \rho_{SED} \eta}\,(1+j) = R + jX \tag{1}$$

where R and X are the specific load resistance and reactance of the sediment. Substituting a complex viscosity $\eta^* = \eta_1 - j\eta_2$, as proposed by Gemant (3), and separating real and imaginary parts gives

$$\eta_1 = \frac{2RX}{\omega \rho_{SED}} \quad \text{AND} \quad \eta_2 = \frac{R^2 - X^2}{\omega \rho_{SED}}$$

where η_1 is the normal flow viscosity and η_2 is an elastic viscosity term which vanishes for normal fluids. Using the identity $G^* = j\omega\eta^*$, where $G^* = G_1 + jG_2$ is the complex shear modulus, gives

$$G_1 = \frac{R^2 - X^2}{\rho_{SED}} \tag{2}$$

and $$G_2 = \frac{2RX}{\rho_{SED}} . \tag{3}$$

The resistive and reactive components of the mechanical impedance are determined using the method devised by McSkimin (10). The specific acoustic impedance at a radial position, a, for torsional waves propagating down a radially symmetric rod is given by

$$Z = -j\frac{\mu a k^2}{4\omega}$$

where

$$k^2 = \frac{\rho_{ROD}\,\omega^2}{\mu} + \gamma^2 .$$

In the above ρ_{ROD} is the density of the aluminum rod, μ is the shear modulus of the rod, and γ is the complex propagation constant

$$\gamma = A + jB$$

where A is the attenuation in nepers per centimeter and B is the phase shift in radians per centimeter. With the rod in air it is assumed that the shear stress at the boundaries is zero and, therefore, the impedance and k are zero. From this, the propagation constant in air is

$$\gamma_0^2 = -\frac{\rho_{ROD}\,\omega^2}{\mu} = (A_0 + jB_0) .$$

When the rod is surrounded by the sediment the impedance is not zero and

$$k^2 = \frac{\rho_{ROD}\,\omega^2}{\mu} + \gamma^2 = -(A_0 + jB_0)^2 + (A + jB)^2 .$$

From the above, then, the impedance of the sediment per unit length becomes

$$Z = \frac{\rho_{ROD} V_0 a}{2}(\Delta A + j\Delta B)$$

where $\Delta A = A - A_0$ is the change in attenuation per unit length, $\Delta B = B - B_0$ is the change in phase per unit length, and $V_0 = \sqrt{\frac{\mu}{\rho_{ROD}}}$ is the velocity of propagation in the unloaded rod.

Since the observed attenuation and phase changes are due to the total length of wave travel, the observed changes must be divided by the length $2n\ell_0$, where n is the number of the echo used and ℓ_0 is the length of rod covered by the sediment. This gives

$$Z = \frac{\rho_{ROD} V_0 a}{4n\ell_0}(\Delta A' + j\Delta B') = R + jX$$

where $\Delta A'$ and $\Delta B'$ are the total change in attenuation and phase resulting from immersing the rod in the fluid.

Determination of the velocity of propagation of the wave in the unloaded rod for the pulsed mode was made by measuring the sound frequency change necessary to give a change in the number of wave lengths in the propagation distance by an integral number. Assuming that the velocity is independent of frequency, the pulse in propagating through the rod undergoes a phase shift given by

$$\phi = \omega t$$

where t is the total time delay of propagation. The time delay is given by

$$t = \frac{2n\ell}{V_0}$$

where ℓ is the length of the rod, n is the number of round trips made by the pulse, and V_0 is the velocity of propagation. At any given frequency, f_0, the phase shift is

$$\phi_0 = 2\pi f_0 \left(\frac{2n\ell}{V_0}\right).$$

For successive 2π radians change in relative phase

$$\phi_m = \phi_0 + m 2\pi = 2\pi f_m \left(\frac{2n\ell}{V_0}\right)$$

where m is any integer. Subtracting we obtain

$$m 2\pi = 2\pi \frac{2n\ell}{V_0} \left(f_m - f_0\right)$$

or

$$V_0 = \frac{2n\ell \Delta f}{m}$$

where $$\Delta f = f_m - f_0 \ .$$

Measuring the total frequency change necessary to give m successive 2π radians change of relative phase allows calculation of the velocity, V_0. The velocity was found to vary slightly with frequency, but this variation was less than one per cent and was not a limiting factor in the precision of determining the acoustic impedance of the sediment.

The total change in attenuation, $\Delta A'$, was computed by determining the difference between attenuator readings necessary for echo cancellation (balance between attenuated continuous signal and pulse-echo signal) with the rod first in air and then in the sediment. The change in attenuation in decibels was then converted to nepers.

The total change of phase in radians, $\Delta B'$, was computed from the equality

$$\Delta B' = \frac{2\pi \Delta f'}{\Delta f_1}$$

where Δf_1 is given by $$\Delta f_1 = \frac{\Delta f}{m}$$

as determined in the velocity calculation above, and $\Delta f'$ is the

additional frequency shift required to re-establish balance when the rod is loaded by the sediment.

c) Resonance Method

As an alternate method of determining the complex shear modulus, one which might allow investigation at lower frequencies, a resonance technique was investigated. In this method the same torsional transducer-rod combination was driven in a continuous-wave mode where standing waves were excited in the rod. The input electrical conductance and frequency at resonance (point of maximum conductance) were measured first with the rod in air and then with it immersed in the sediment. From these measurements the change in electrical resistance (ΔR_E) and the change in the resonant frequency (Δf_R) were calculated. Under the assumption that the relationships

$$\Delta R_E = K_1 R \quad \text{AND} \quad \Delta f_R = -K_2 X ,$$

developed for a torsional transducer submerged in a viscous liquid (8), hold for this case we may then calculate the complex shear modulus (Equations 2, 3). The constants K_1 and K_2 may be determined by measurements using Newtonian fluids of known viscosity. Here R and X are the resistive and reactive components of the mechanical impedance of the sediment (Equation 1).

3. Equipment and Procedures

a) Details of Equipment

The transducer-rod combination used in this research, one constructed and used previously by Prather (11), consists of a one-half inch diameter, one and one-half inches long barium titanate torsional transducer cemented to an aluminum rod of the same diameter and about

1 meter in length.

In this experiment, prolonged immersion of the rod in the sediment was required and during preliminary measurements it was found that the aluminum rod became highly corroded. For this reason the rod was coated with metal lacquer. A dipping procedure was used to obtain a uniform coating.

The rod was supported by needle pivot bearings inside a water jacketed pipe which could be filled with the sediment to be tested (see Figure 4). A brass base plate with a needle pivot attached was fastened to the bottom of the pipe with machine screws and sealed with an "O"-ring. The base plate was designed for easy removal to facilitate placement of the rod and cleaning the pipe. The top of the pipe was left open for filling. The needle pivot bearing at the top was supported by a clamp fastened to the main support stand. Temperature control of the water jacket was provided by a thermally controlled water bath and pump unit capable of maintaining the sample temperature at $25^{\circ} \pm 0.1^{\circ}$ C. This temperature deviation was not considered a limiting factor in the experimental accuracy.

The equipment setup used for the pulse measurement technique is shown in Figure 1 in block diagram form. The sinusoidal signal from the oscillator is amplified and connected in parallel to the attenuator, tone-burst generator and the frequency counter. The path through the attenuator to the oscilloscope provides a direct continuous reference signal for phase and amplitude cancellation of the pulse. The path through the tone-burst generator provides the pulsed driving signal for the torsional transducer. The isolation gate (Gate A) following the tone-burst generator provides -40 db of isolation of the cut-off (inter-

pulse) signal from the continuous signal in addition to -40 db provided by the tone-burst generator. The total isolation for the tone-burst generator and gate combination is, therefore, -80 db. Gate B following the transducer is a blanking gate which prevents the main pulse from reaching the oscilloscope. This allows use of the maximum gain of the oscilloscope's vertical amplifier without saturation. A detailed diagram of the gate-transducer-gate combination is shown in Figure 2. The transistor of Gate A (PNP) and the transistor of Gate B (NPN) are triggered simultaneously by the gating voltage output from the tone-burst generator. During the interval of the main pulse Gate A is open (forward bias) allowing the signal to reach the transducer and Gate B is closed (reverse bias) preventing the main pulse from reaching the oscilloscope. During the interval between the driving pulses Gate A is closed providing the necessary isolation and Gate B is open allowing the received echo pulses to be displayed on the oscilloscope. The oscilloscope was a dual input cathode ray oscilloscope which allowed an independent display of the received echo train and the direct attenuated signal or a display of the sum of the two inputs. The oscilloscope sweep system was triggered by the tone-burst generator.

The tone-burst generator was operated using a 16 cycle pulse and a pulse repetition rate which allowed sufficient time for decay of each echo train to below the noise level. The direct continuous reference signal was attenuated using a 600 ohm noninductive attenuator capable of measuring 0.1 db steps. Frequency was measured using a five decade counter with a 10 second gate.

A block diagram of the equipment setup used for the resonance technique is shown in Figure 3. The signal from the oscillator is amplified

and fed directly to the complex impedance-admittance meter (Dranetz Engineering Laboratories Model 100B) and the five decade frequency counter. The transducer is connected directly to the meter. Operated in the admittance mode the meter gives a direct reading of the input electrical conductance and susceptance of the transducer.

Regulated line voltage for operation of the oscillator, amplifier, admittance meter, and tone-burst generator was supplied through a constant voltage transformer. This was necessary to insure adequate stability of the oscillator and to reduce the overall system noise level. To provide additional stability the oscillator was left in continuous operation with no load between measurements. (Frequency drift was approximately 2 parts per million per hour.) All other equipment was turned on at least one hour prior to making measurements.

b) Procedures

In preparation for the pulse measurements, the sum of the continuous and pulse-echo signals was displayed on the oscilloscope using sufficient horizontal and vertical gain to give as large a display of the desired echo as possible. The use of the third or higher numbered echo was suggested by Prather (11) as a means of obtaining more precise attenuation measurements. Measurements were made using the third, fourth, fifth and sixth echoes. Measurement of the frequencies and attenuations necessary for echo cancellation with the rod in air were made and recorded over the frequency range of 33.3 kHz to 42.3 kHz. With the rod still in air the equipment connections were changed and measurement of the resonant frequencies and the maximum conductances were made and recorded over the frequency range of 30 kHz to 43 kHz for the resonance method. The sediment and water mixture was then poured

into the water jacketed pipe and allowed to stand for 1 or 2 days. This was necessary to allow thermal equilibrium to be reached but primarily to allow the sediment to settle enough so that no measurable change in the properties would occur during the length of time required to make a set of measurements. When this condition was reached the measurements of frequency and attenuation necessary for echo cancellation in the pulse method and the measurements of resonant frequency and maximum conductance in the resonance method were repeated over the same frequency ranges. For the pulse method the changes in frequency and attenuation were converted into changes of phase in radians and attenuation in nepers. From these values the resistive and reactive loading of the sediment could be calculated. For the resonance method the maximum conductances were converted to resistances to obtain the changes in electrical resistance in ohms. From these values and the changes in the resonant frequency the resistive and reactive loading of the sediment could be calculated using the constants K_1 and K_2. These constants were evaluated by making the measurements described above in standard Newtonian ($R = X$) liquids of known viscosity. Pulse and resonance measurements were made on five liquids of different viscosities and the constants were evaluated for each liquid. The final values of the constants were obtained by averaging the individual values.

As indicated above, measurements for the pulse method were made over the frequency range of 33.3 kHz to 42.3 kHz and for the resonance method over the frequency range of 30 kHz to 43 kHz. In making calculations for the final results, however, it was found that the agreement between methods decreased with deviation from the primary resonance frequency of the transducer. Because of this only those measurements

taken near the primary resonance (38.3 kHz to 38.9 kHz for the pulse method and 37.7 kHz to 39.3 kHz for the resonance method) were used in obtaining the final results. In both methods the frequency range implies two measurements at the extremes the results of which were averaged to obtain the final results for the individual method. These results are then said to apply over their respective frequency ranges, since the difference at the extremes was on the order of ten percent.

In addition to the effect noted above a slightly different frequency response was obtained for each individual echo (i.e. third, fourth, fifth and sixth echoes). Because of this, correlation between the measurements obtained for the individual echoes was not made. Since the measurements in the standard fluids were made using only the third echo, the measurements made on the later echoes were not used to obtain the final results.

c) Sediment Preparation

The sediment used in these experiments was commercially available Kaolin, N.F. Kaolin is a clay mineral (aluminum disilicate) which is found extensively in natural sediments, and has been used previously in other acoustic measurements (6). It was obtained in a very fine powder form which was found to be quite workable. When mixed with water a smooth homogeneous mixture was easily obtained.

To prepare the sediment a known weight of kaolin powder was mixed with sufficient water to obtain a smooth homogeneous mixture which was then boiled at atmospheric pressure to allow the escape of entrapped and dissolved gases.

When visible signs of the escaping gases had subsided the sediment-water mixture was allowed to cool. The mixture was then weighed and

the percentage weight of dry Kaolin per unit total weight was calculated. (This percentage concentration by weight was used in determining the porosity in a manner which will be explained later in the section.)

In conjunction with filling the pipe with the water-saturated sediment a glass tube was filled with the same mixture to the same height as that in the pipe. The diameter and weight of the glass tube were known, the height of the sediment could be measured and the glass tube and sediment could be weighed. Thus the density of the sediment could be computed at any time. The glass tube also allowed visual observation of the settling process. The fact that the heights of the sediment columns were equal assured that the settling rate and density of the sediment in the glass tube could be used as a measure of the conditions in the pipe. As the settling process proceeded under gravity an increasing amount of pure water collected at the top of the column. A correction for this amount of pure water was made in the density calculations for the sediment. Similarly, it was not included in the length of rod in the material (ℓ_0).

In preparation for a comparison of values obtained for the shear modulus to be made in the results section the porosity of the sediment was determined as follows. Porosity is defined as the percentage volume of voids per unit total volume. In terms of known quantities the porosity, P, is given by

$$P = \left[\frac{\rho_{SED}}{\rho_{WATER}} - \frac{\text{WEIGHT OF SOLID}}{\rho_{WATER} \times \text{TOTAL VOLUME}} \right] \times 100\,\%$$

where the weight of solid material is computed from the total weight of the water-saturated sediment and the percentage concentration by weight

obtained earlier in the section.

4. Results and Conclusions

The values of the constants K_1 and K_2 evaluated by making both pulse and resonance measurements on the standard fluids are tabulated in Table 1. Also included are the average values of the constants.

The results of the resonance method are tabulated in Table 2. Data were available from two sets of measurements taken one week apart on the same sediment sample. For each set of measurements the resistive and reactive components of the mechanical impedance were calculated using the average values of the constants K_1 and K_2 from Table 1.

Data for the pulse method were available from the same two sets of measurements that were used to obtain the resonance data. The results of the pulse data are tabulated in Table 3. From the values obtained for the real and imaginary components of the complex shear modulus it is apparent that the sediment investigated does exhibit both viscous and elastic properties over the very limited frequency range investigated. The order of magnitude increase in the rigidity, G_1 , of the sediment over the one week time lapse between measurements indicates that the properties of the sediment change rapidly with increased compaction. The change in porosity between the two sets of measurements can be seen to be only about three percent.

The agreement, within the experimental accuracy, of the values of the resistance and reactance of the sediment obtained using the two independent measurement techniques indicates that both of the methods used are valid at least over the limited range of values obtained for the complex shear modulus and at the frequencies investigated.

Hamilton (4) calculated values for the rigidity (G_1) of the order

of 10^9 dynes per square centimeter using "in situ" measurements of the velocity of longitudinal waves in shallow water sediments. The porosities reported by Hamilton were, on the average, slightly lower than those reported here and the sediments were natural sediments with a distribution of grain sizes.

Bucker (1) used assumed values for the imaginary part of the complex shear modulus (G_2) of the order of 10^8 to 10^{11} dynes per square centimeter to obtain reasonable agreement between calculated and experimental bottom losses for natural ocean sediments.

These comparisons are intended to indicate the order of magnitude of the complex shear modulus used for natural sediments and not expected to agree with the values reported here. The sediment used in this research was intended only as a convenient laboratory substitute for real ocean sediments.

5. Discussion of Error

The estimated overall system error is 10%. The primary factor in determining this error was the precision with which a particular set of measurements could be repeated. The precision with which frequency measurements could be made was $\pm$ 2 cycles per second. For attenuation measurements the precision was $\pm$ 0.2 decibels. The effect of these uncertainties on the results was determined and from these effects the estimated error was obtained.

It is believed that the error could be reduced by: (1) using highly polished stainless steel rods which would be less susceptible to corrosion, (2) improving the temperature regulation, and (3) immersing the entire length of the rod into the material to obtain a constant and to minimize reflections at the surface of the sediment.

STANDARD LIQUID	K_1	K_2
Antifreeze	0.65	0.0016
Ethylene Glycol	0.62	0.0017
Cottonseed Oil	0.70	0.0016
Medium Lubricating Oil	0.70	0.0018
Castor Oil	0.72	0.0017
Average	0.68	0.0017

Table 1. CONSTANTS EVALUATED FOR RESONANCE METHOD

MEASUREMENT	ΔR_E $\times 10^3$	Δf_R	R	X
First	12.9	23.0	235	167
Second	37.7	13.8	737	107

Table 2. RESULTS OF RESONANCE METHOD FOR THE FREQUENCY RANGE 37.7 to 39.3 kHz. $R_E \times 10^3$ IS GIVEN IN OHMS, f_R IN CYCLES PER SECOND, AND R AND X IN GRAMS/cm^2-SEC.

MEASUREMENT	R	X	G_1	G_2	P
First	284	158	4×10^4	6×10^4	78%
Second	816	95	4×10^5	11×10^4	75%

Table 3. RESULTS OF PULSE METHOD FOR THE FREQUENCY RANGE 38.3 to 38.9 kHz. R AND X ARE GIVEN IN GRAMS/cm^2-SEC, G_1 AND G_2 ARE GIVEN IN DYNES/cm^2, AND P IS GIVEN IN PERCENTAGE VOLUME OF VOIDS PER UNIT TOTAL VOLUME.

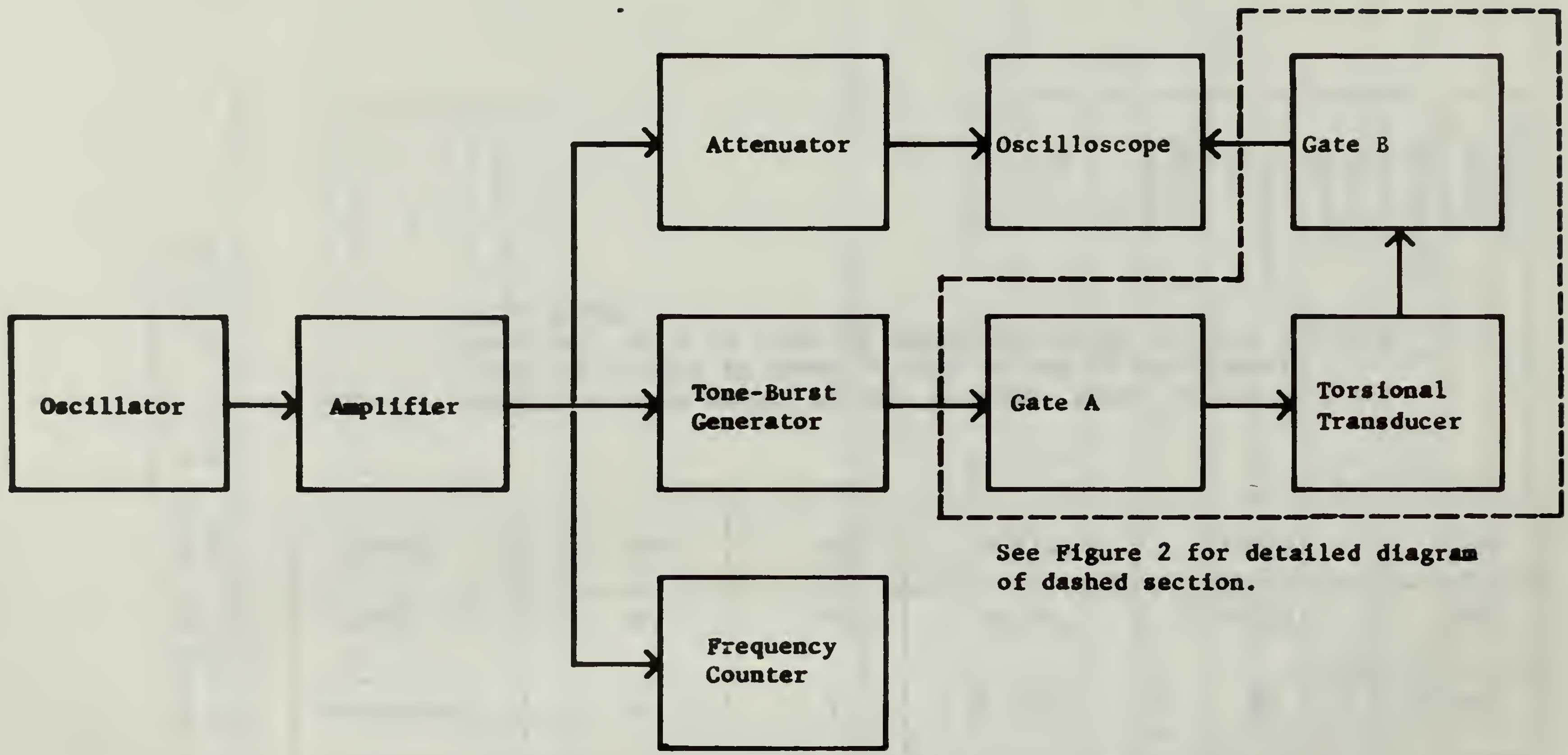

FIGURE 1. BLOCK DIAGRAM OF EQUIPMENT SETUP FOR PULSE METHOD

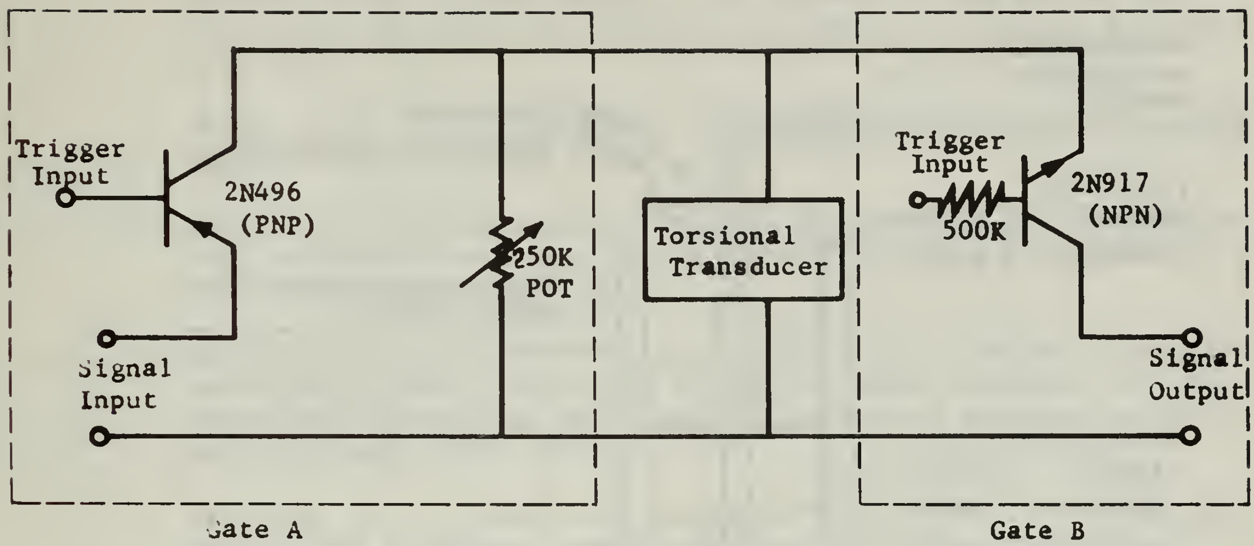

FIGURE 2. DETAILED DIAGRAM OF GATE SYSTEM

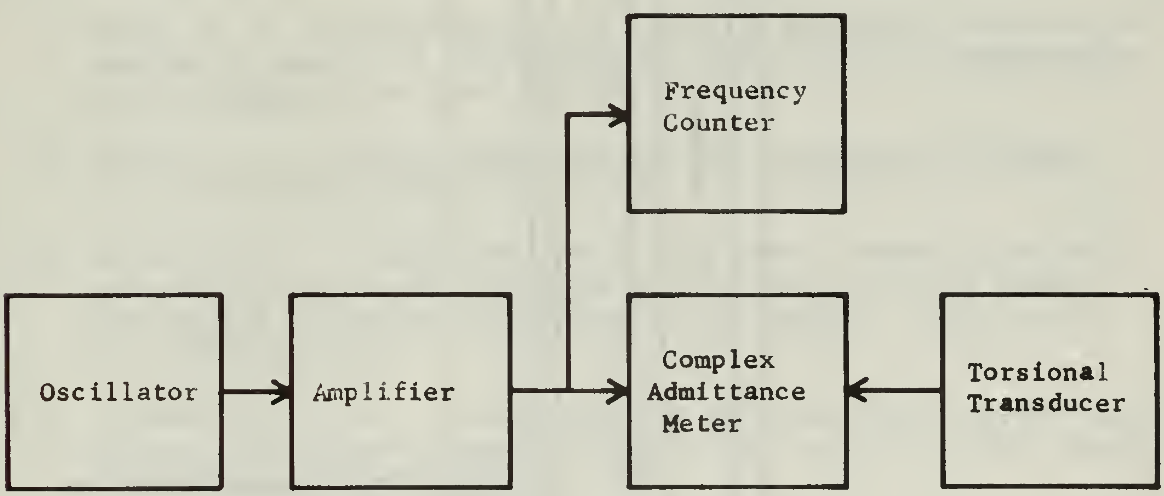

FIGURE 3. BLOCK DIAGRAM OF EQUIPMENT SETUP FOR RESONANCE METHOD

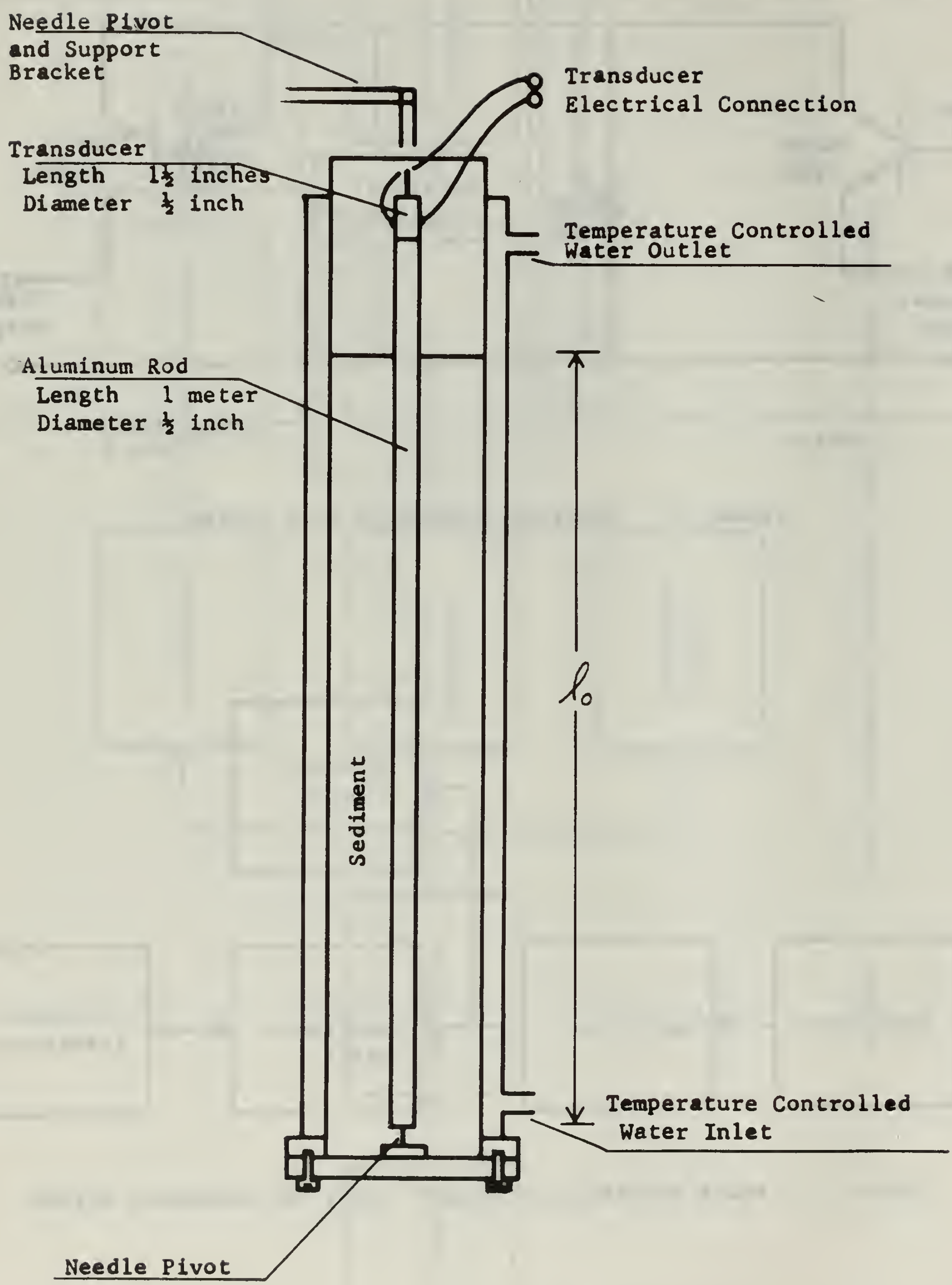

FIGURE 4. CUTAWAY VIEW OF WATER JACKETED PIPE AND TRANSDUCER-ROD COMBINATION

BIBLIOGRAPHY

1. Bucker, H. P., J. A. Whitney, G. S. Yee, R. R. Gardner. Reflection of Low-Frequency Sonar Signals from a Smooth Ocean Bottom, The Journal of the Acoustical Society of America, v. 37, no. 6, June 1965, 1037-1051.

2. Ewing, W. M., W. S. Jardetzky, F. Press. Elastic Waves in Layered Media, McGraw-Hill Book Company, Inc., 1957.

3. Gemant, A. The Conception of a Complex Viscosity and Its Application to Dielectrics, Transactions of the Faraday Society, v. 31, 1935, 1582-1590.

4. Hamilton, E. L., G. Shumway, H. W. Menard, C. J. Shipek. Acoustic and Other Physical Properties of Shallow-Water Sediments Off San Diego, The Journal of the Acoustical Society of America, v. 28, no. 1, January 1956, 1-15.

5. Hamilton, E. L. Geoacoustic Models of the Sea Floor. 1. Shallow Bering Sea; 2. Mohole (Guadalupe Site), U.S. Navy Electronics Laboratory Report 1283, April 1965.

6. Hampton, L. Acoustic Properties of Sediments, Defense Research Laboratory Acoustical Report No. 254, August 1966.

7. Laughton, A. S. Sound Propagation in Compacted Ocean Sediments, Geophysics, v. XXII, no. 2, April 1957, 233-260.

8. Mason, W. P. Measurement of the Viscosity and Shear Elasticity of Liquids by Means of a Torsionally Vibrating Crystal, Transactions of the A.S.M.E., May 1947, 359-370.

9. Mason, W. P. Physical Acoustics and the Properties of Solids, D. Van Nostrand Company, Inc., 1958.

10. McSkimin, H. J. Measurement of Dynamic Shear Viscosity and Stiffness of Viscous Liquids by Means of Traveling Torsional Waves, The Journal of the Acoustical Society of America, v. 24, no. 4, July 1952, 355-365.

11. Prather, R. J., Jr. Investigation of the Ultrasonic Dynamic Viscoelastic Properties of Aqueous Polyethylene Oxide Solutions, Thesis, Naval Postgraduate School, May 1966.

12. Shumway, G. Sound Speed and Absorption Studies of Marine Sediments by a Resonance Method--Part II, Geophysics, v. XXV, no. 3, June 1960, 659-682.

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13. ABSTRACT

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	ROLE	WT	ROLE	WT	ROLE	WT
Sediments						
Viscoelastic						

[redacted]